Computational Materials Science 50 (2011) 3145–3152

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Targeted material design of flyash filled composites for friction braking application by non-linear regression optimization technique

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ARTICLE INFO

Article history:
Received 12 May 2011
Accepted 29 May 2011

Keywords:
Wear
Polymer matrix composite
Flyash

ABSTRACT

Targeted material design (TMD) following combinatorial engineering approach based on experimentally determined performance defining attributes (PDA) of a series of heterogeneous friction-composites is attempted via non-linear regression optimization (NLR-OPT) technique. The four key PDAs have been rigorously evaluated on a Krauss friction testing machine. The four selected performance defining attributes (PDA) are performance-friction, wear, friction-fade and friction-recovery. Based on the performance data two target-composite formulations are designed adhering to friction-maximization norms. The theoretically obtained formulation designs for a target set of PDA were later validated by fabricating actual composites followed by their performance assessment on identical testing set-ups and test-regulation. The two targeted composite formulations were also replicated for flyash derived cenospheres in addition to the raw flyash based composites. Finally, the deviations in PDA are critically analyzed from material composition point of view and the adopted approach gives rise to minimal deviation from the magnitude of theoretically estimated PDA. The study has successfully demonstrated that non-linear regression technique based optimization for targeted material design of heterogeneous composites with multiple performance goals may prove to be a sound and viable engineering approach for material designers.

1. Introduction

Designing of hybrid composite materials based on multiple and functionally disparate ingredients for heavy duty engineering applications such as in friction braking are a well known problem of multi-criteria objective optimization [1–3]. Research in the area of friction material development is based on randomly chosen friction formulations with many chemically dissimilar ingredients [4,5]. These ingredients may broadly be of four classes that are binder, filler, fiber and friction modifiers [6]. Reaching at a successful friction formulation is often complex and involves tedious task of fabrication, characterization and performance evaluation of a large number of composites that may tentatively be equal to the possible permutations and combinations of the number of ingredients that are used. For example, a friction formulation with 15 ingredients may be optimized only by fabricating and tribo-evaluating $15! = 1.3 \times 10^{12}$ number of composites, if one-variable-at-a-time (OVAT) experimental design is strictly followed. Therefore the conceptual issue of reaching at a desired formulation of friction material with a targeted set of performance defining attributes (PDA) may be tackled by resorting to several composite formulation optimization methods based on stochastic designs where the randomization of the performance attributes is deliberately carried out in order to generate a gray performance data base [7,8]. Such data base forms the basis of further analysis within the realms of several optimization theories, such as, multi-criteria decision making (MCDM) [2], multi-attribute decision making (MADM) [9], multiple objective decision making (MODM) [10], gray relational analysis (GRA) [7], gray target theory (GTT) [11], analytical hierarchy process (AHP) [12,13], technique for order preference by similarity to ideal solutions (TOPSIS) [3], elimination and choice translating reality (ELECTRE) [14], Golden section rule [15,16], Genetic algorithm [8], artificial neural network (ANN) [17], linear and non-linear regression methods [18] and Taguchi analysis [19]. Most of the decision support based models are subjectively evaluated. For example, Gray statistics theory involve relatively linear approximations [7,20], AHP and TOPSIS involve deviation/approaching degree with respect to an objective performance/formulation ideology [13,21] whereas GA and ANN models remain inherently sensitive from accuracy point of view, often due to the limited number of training data sets [8,17]. Non-linear approach has empirically been considered to be more appropriate though their realistic validation pertaining to friction materials is not yet

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doi:10.1016/j.commatsci.2011.05.043

attempted. An optimization method based on Chemometrics principles involving non-linear optimization has already been reported to be fairly successful in enabling the product designers to develop targeted materials with a pre-defined performance ideology [22].

Flyash with the ability to enhance the specific performance along with abrasion resistance, porosity serve as promising and cost-reducing functional filler for augmenting tribological performance of filled composites such as brake friction materials [23–26]. The relevance of flyash as a filler in friction materials becomes even more important considering the fact that these composites integrally consist of ~50–60% of space filler/inert or non-functional filler such as barites and lime-stone [27]. The techno-commercial viability can only be realized when the performance requirements are not compromised, especially for a critical automotive component like brake. Because of the disparate nature of the quality of the coal that varies with mines and the differential combustion efficiency of the coal in the various thermal power plants, performance aspects always need to be assured [28]. Therefore multiple formulation designs will be the key to develop friction materials based on flyash that may vary in its composition either due to the geographical region-specificity or due to non-uniformity in the degree of combustion. Hence to address this problem of hitting at the formulation for a set of designed performance requirements the prior performance data dealing with influence of flyash in combination with other ingredients in various combinations need to be analyzed. Such an objective may theoretically be manipulated by resorting to standard statistical models/operation research principles where the closest possible performance criteria may be approximated though they need further validation by fabrication and real evaluation of the materials on the standard testing systems. Adding to the complications of performance prediction and analysis is the stochastic nature of tribological processes which may decisively alter PDA by inducing topographical variations [29] and other shear induced thermo-mechanical phase transitions at the braking interface [30,31]. However, efforts to systematically analyze the factors influencing the PDA including compositional variables and their interdependence while ensuring the performance-reliability is crucial to design a pre-defined targeted friction material. In this investigation, reaching at two sets of objective design alternatives (conforming to a set of fixed performance defining attributes) of friction material formulation via non-linear regression approach has been attempted. The validation of the designed composites based on optimization principles have also been carried out by developing and assessing the performance of real-time composites.

2. Background of the performance data and non-linear regression optimization

In our earlier investigations the performance assessment of eight composites with four compositional variables namely, PF resin, flyash, lapinus fiber and aramid fiber have been carried out and was critically analyzed [25,26]. The formulations of the eight composites are given in Table 1.

The performance properties are correlated to nature of the composition, the thermal characteristics, and the wear surface topographic attributes. Based on the performance defining attributes of the investigated eight compositions non-linear regression analysis is attempted in the current context with an objective to establish a quantitative correlation between the type of the ingredients that are varied in their level of incorporation into the various composites and the four key performance defining attributes (PDA) i.e. performance-μ, fade, recovery and wear. The details of the PDA for the eight evaluated composites as the primary data set are given in Table 2.

For all the composites, the weight proportion of aramid pulp was constant at 5%. The three variable ingredients were designated as x, y and z for PF resin, flyash, and lapinus fibers respectively. Non-linear equations of the following forms were developed and were put to a fit for each of the friction material properties/performance defining attribute (PDA) namely performance-μ, wear, fade and recovery. The adopted generalized form of non-linear equation correlating PDA and the extent of variable ingredients is as given in the following equation:

$$\mathrm{PDA} = A + B\cdot x + C\cdot y + D\cdot z + E\cdot x^2 + F\cdot y^2 + G\cdot z^2 \quad (1)$$

where $A, B, \ldots, G$ are the regression coefficients determined by the least square techniques. Seven normal equations (Eqs. (2)–(8)) were developed, as shown below, to determine the values of coefficients $A, B, \ldots, G$ using the PDA data of eight composites shown in Table 3.

$$\sum \mathrm{PDA} = n\cdot A + B\sum x + C\sum y + D\sum z + E\sum x^2 + F \times \sum y^2 + G\sum z^2 \quad (2)$$

$$\sum \mathrm{PDA}\cdot x = A\sum x + B\sum x^2 + C\sum xy + D\sum xz + E\sum x^3 + F\sum xy^2 + G\sum xz^2 \quad (3)$$

$$\sum \mathrm{PDA}\cdot y = A\sum y + B\sum xy + C\sum y^2 + D\sum yz + E\sum x^2y + F\sum y^3 + G\sum yz^2 \quad (4)$$

$$\sum \mathrm{PDA}\cdot z = A\sum z + B\sum xz + C\sum yz + D\sum z^2 + E\sum x^2z + F\sum y^2z + G\sum z^3 \quad (5)$$

$$\sum \mathrm{PDA}\cdot x^2 = A\sum x^2 + B\sum x^3 + C\sum x^2y + D\sum x^2z + E \times \sum x^4 + F\sum x^2y^2 + G\sum x^2z^2 \quad (6)$$

$$\sum \mathrm{PDA}\cdot y^2 = A\sum y^2 + B\sum xy^2 + C\sum y^3 + D\sum y^2z + E \times \sum x^2y^2 + F\sum y^4 + G\sum y^2z^2 \quad (7)$$

Table 1
Details of the composites and their designations for primary performance data set evaluation.

Ingredients wt.%	Flyash friction composite (FFC) designations							
	FFC-1	FFC-2	FFC-3	FFC-4	FFC-5	FFC-6	FFC-7	FFC-8
PF Resin[a] (x)	20	25	30	35	15	15	15	15
Flyash[b] (y)	75	70	65	60	55	60	65	70
Lapinus fiber (z)	0	0	0	0	25	20	15	10
Kevlar pulp	5	5	5	5	5	5	5	5

[a] PF resin: Novolac type straight phenol–formaldehyde resin.
[b] The minimum flyash was kept at 55 wt.% with the objective of maximum utilization.